NUMERICAL SIMULATION OF AN AUV THRUSTER DURING MANEUVERING

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ABSTRACT

Preliminary results are presented from a numerical study of the unsteady hydrodynamics of an AUV thruster. A vortex-lattice, lifting-surface model, developed originally for ship propellers operating under normal design conditions at constant angular velocity, is modified to handle unsteady operating conditions of an AUV thruster during dynamic positioning and maneuvering. The present numerical code applies to an unducted propeller though the method can be modified to handle ducted propellers. The results from sample runs of the thruster undergoing step changes and sinusoidal oscillations in the angular velocity of the propeller are shown.

KEY WORDS: AUV thruster, unsteady propeller hydrodynamics.

INTRODUCTION

The motivation of this research is to develop an accurate hydrodynamic model of an AUV thruster during unsteady operations. Such a model could be used to develop controllers for vehicles that operate in the ocean and are subjected to large time-varying forces. For example, the large oscillating wave forces that dominate near-shore and near-surface ocean environments will cause an underwater vehicle to move back and forth with horizontal and vertical amplitudes of the order of meters and with time scales of the order of seconds. To maintain a prescribed course under closed-loop control, the thrusters will have to continually switch from forward to reverse thrust and back again to forward thrust in such a way as to negate the effects of wave and current forces as well as the inertial forces of the vehicle. The correct timing of this control action is possible only if there is an accurate model of the thruster dynamics and hydrodynamics built into the controller.

When a dynamic positioning controller commands a certain amount of thrust using present-day methods, the desired thrust does not occur instantaneously because of time delays involving the fluid inertia and velocity of the fluid flowing over the propeller blades. Consider a propeller operating with a steady-state angular velocity Ω and forward thrust T. If the angular velocity is suddenly reversed to $-\Omega$, the fluid surrounding the propeller will still be flowing in the original direction. With time, the fluid reverses course and eventually reaches a steady-state flow velocity equal to the original value but in the opposite direction (assuming that the thruster is symmetric for forward and reverse operations). The thrust also reverses direction and becomes equal to $-T$ at steady state. This process of reversing thrust from the original command to the actual application of the desired value can take a number of seconds on an AUV, enough of a delay to cause a characteristic limit cycle which reduces tracking performance in dynamically positioned vehicles.

Yoerger *et al.* (1990) were the first to recognize that thruster dynamics were responsible for limit cycles in the context of dynamic positioning of underwater vehicles. They proposed a first order dynamic model to describe this phenomenon. The model includes a term in the momentum equation that is linearly related to the angular acceleration of the motor shaft as well as the square of the shaft angular velocity. The inertia coefficient, which is found from experiments, implicitly accounts for the added mass of the fluid. However, this model ignores the effect that fluid flow has on the instantaneous angle-of-attack.

Healey *et al.* (1994) derived a second order model that uses the angular velocity of the propeller shaft and the axial fluid velocity as state variables. This formulation permits the angle-of-attack of the propeller blade to vary with time. Simulations using the model showed that the prediction of both steady-state and transient responses was improved. Whitcomb and Yoerger (1995) simplified this model by writing it as a one dimensional system with the axial fluid velocity as the state variable and the angular velocity of the propeller as the control input.

The accurate real-time measurement of axial flow velocity could be used with the model of Whitcomb and Yoerger (1995)

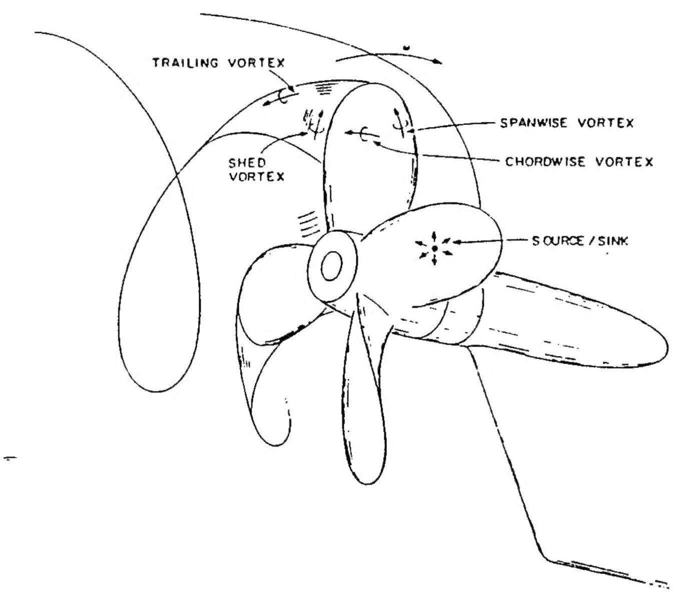

Figure 1: Schematic of propeller and wake with distributed sources and vortices (from Kerwin and Lee 1978).

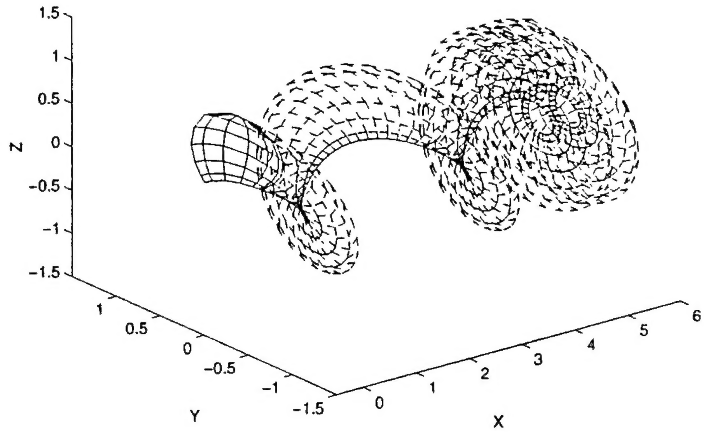

Figure 2: Numerical simulation of development of vortex wake sheet behind a single bladed propeller operating with variable angular velocity. The wake trails from the propeller at the left to downstream on the right. The initial calculations (represented by the farthest downstream sections of the helical vortex sheet) correspond to 500 RPM. The angular velocity was then reduced to 100 RPM causing the coils of the wake to spread.

to design a thrust controller. However, it is not practical to measure the fluid velocity near the propeller blade of an AUV operating in the ocean. This is where the numerical hydrodynamic model for the thruster could prove useful. It would be used to construct an observer that estimates the fluid velocity from the past history of the propeller's angular velocity and motor torque (which is proportional to the electric current) both of which are easily measured in real time. The accuracy of the observer, then, depends on the accuracy of the hydrodynamic model.

DESCRIPTION OF NUMERICAL MODEL

The numerical model is based on the vortex-lattice, lifting-surface theories developed at Massachusetts Institute of Technology and reported in Kerwin and Lee (1978) and Keenan (1989). In this formulation, the propeller geometry and flow field are represented by a set of sources and vortices distributed on the mean camber surface of each blade and a distribution of vortices shed into the wake (Fig. 1). The strengths of the sources and vortices as well as the location of the shed vortices vary with time and can be determined from the "no-flow" boundary condition of the propeller (i.e. the normal flow velocity is zero on the propeller blades) and the "no-jump" pressure condition on the wake vortex sheet (i.e. the fluid pressure is continuous across the vortex sheet).

Keenan (1989) developed vortex-lattice methods to simulate the dynamics of a thruster subjected to a spatially varying and time invariant in-flow current. In this scheme, vorticity is shed at each time step from the tip and trailing edge of the propeller into the wake. The strength of the shed vorticity will change due to the varying position of the blade and in-flow velocity. Since, the pattern repeats itself every revolution of the blade, an steady-state oscillatory pattern develops in the wake.

We have recently extended the method so that the in-flow current and the angular velocity of the propeller can vary with time. Fig. 2 shows a sample calculation of the development of the wake due to a step change in the angular velocity from 500 to 100 revolutions per minute (RPM) and vehicle velocity of 2.5 m/s.

Our time-variant model is presently limited to an unducted propeller and none-reversing flow. Ducted propellers have been simulated in spatially varying and time invariant flows using vortex-lattice methods (Hughes 1993), and it is a straight forward extension to temporally varying the in-flow currents and propeller angular velocity. Reverse flow is more difficult to implement because of the need to track the vortex sheet as it is pulled back through the propeller. Our future work will involve developing a model that permits each vortex segment to have compact support and convect independently (Anderson and Greengard 1985). Though this scheme would fail to simulate the turbulence that would develop during the "ingestion" of the vortex sheet, it will help us understand the large-scale dynamics of the process.

Another limitation of the numerical code, in its present form, is its ability to simulate operating conditions that are away from the design conditions of the thruster as defined by the advance coefficient of a propeller which is defined as:

$$J = \frac{U}{nD} \tag{1}$$

where U is the ambient fluid velocity due to vehicle motion and current, n is the angular velocity of the propeller, and D is the diameter of the propeller. Typical propellers are designed to operate at a specific value of J. AUV thrusters on the other hand operate over a range of J-values. Because of this, large angles of attack are possible as well as separation about the leading edge of the propeller blades. Further modifications of the numerical code will include this effect through the modification of the leading-edge suction force (Keenan, 1989).

SAMPLE CALCULATIONS

In this section, we present results from three separate simulations.

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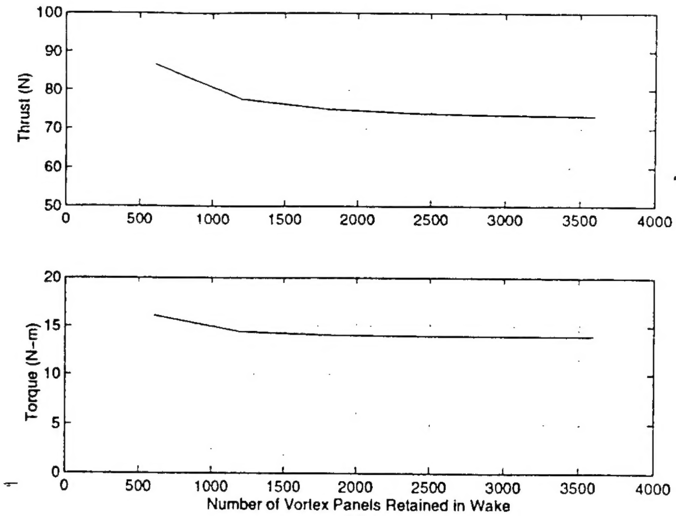

Figure 3: Convergence of steady-state solution as a function of number of vortex panels in the wake. The angular velocity of the propeller is 700 RPM and the flow velocity is 1.5 m/s.

The first is a propeller operating under steady conditions. The second simulation is a propeller undergoing sinusoidal variations of its angular velocity about a steady-state operating condition. The final case is a step test where the angular velocity and flow velocity is increased instantaneously from zero to a finite value.

The propeller that we model is a three-bladed propeller with a diameter of 24 cm manufactured by Vetus Corporation (model number BP125). This is the same propeller that is used on the JASON ROV, and it was used in the experiments of Whitcomb and Yoerger (1996).

Steady-State

The steady-state case is meant to verify the stability of the code and to determine at what point the wake should be truncated downstream. The simulation begins by initially specifying an ambient flow velocity U, the propeller's angular velocity Ω, the number of vortex panels on the blades, and the number of panels that make up the wake. Next, we calculate the steady-state solution using a steady-state code by adjusting the strength of the vortex panels on the blade and in the wake in order to satisfy the "no-flow" boundary condition on the blade and the "no-flow" condition of the wake (Kerwin and Lee, 1978). Finally, we take this solution as the starting point of a time-domain simulation. We move the propeller a fraction of a revolution (in this case 12^o), shed the row of vortex panels off the trailing edge into the near wake, convect them downstream, and remove the row of vortex panels from the far-end of the wake. If our time-domain code is stable, then the steady state solution will persist for all time, which it does.

Fig. 1 presents the results for the case of $U = 1.5$ m/s and $\Omega = 700$ revolutions per minute (RPM). The length of the simulation is 1.5 s. The number of panels used in the wake is varied in order to determine when the code converges. Since truncating the wake is an approximation, the length of the wake will effect the accuracy of the calculations. Here convergence is achieved with 2400 panels based on the values of the thrust and torque.

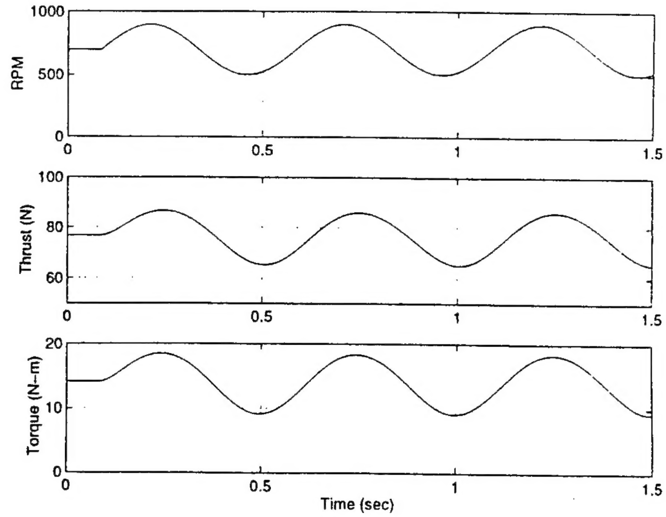

Figure 4: Thrust and torque of a propeller undergoing sinusoidal variations of the propeller's angular velocity about a mean operating condition. The mean angular velocity is 700 RPM and the amplitude of the variation is ± 200 RPM. The flow velocity is 1.5 m/s.

Sinusoidal Variation of Propeller RPM

For this case, the initial conditions are the same as for the previous steady-state simulation with a wake length of 2400 panels. The simulation proceeds as before for one propeller cycle after which the value of Ω is varied sinusoidally from 500 RPM to 900 RPM with a period of 0.5 seconds which is one-half of a propeller revolution at the nominal angular velocity of 700 RPM. The results of the simulation show a time lag between the peaks of the angular velocity and the peaks of the thrust and torque curves (Fig. 4). The mean values of the thrust and torque match the steady-state values.

Step Test

The step test involves an instantaneous jump from $\Omega = 0$ and $U = 0$ at time $t = 0$ to $\Omega = 700$ RPM and $U = 1.5$ m/s. The initial shape of the wake is taken as the steady-state solution with 2400 vortex panels, but the initial strengths of the vortex panels are set equal to zero. During the first time step, the first row of vortex panels that is shed into the wake is strong. This starting vortex influences the solution while it is in the near wake, loses influence as it convects downstream, and has no influence once it drops off the end of the truncated wake. This is seen in the thrust and torque results (Fig. 4).

The peaks in the thrust and torque curves are due to the influence of the starting vortex which is shed at time $t = 0$. The first peak corresponds to roughly one-third of a propeller revolution and corresponds to the three propeller blades passing the starting vortices shed by the blade that is rotating ahead of it. The next peak at roughly two-thirds of a revolution corresponds to the trailing blades passing the starting vortices which have convected further downstream. A smaller peak at one propeller revolution corresponds to the blades passing their own starting vortices. The thrust and torque values asymtote to the steady-state solution.

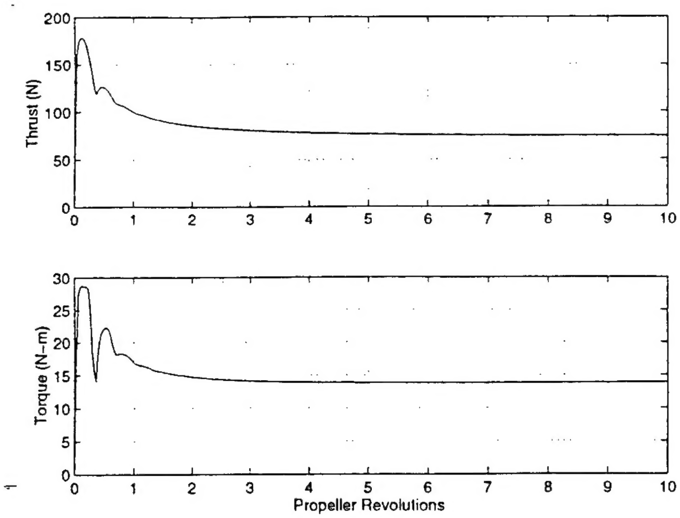

Figure 5: Thrust and torque of a propeller undergoing an instantaneous acceleration from 0 RPM to 700 RPM. The flow velocity is assumed to go instantly from 0 m/s to 1.5m/s.

SUMMARY AND CONCLUSIONS

We have begun a research program to simulate the hydrodynamics of an unsteady AUV thruster with the unsteadiness arising from temporal changes in the inflow velocity and the propeller's angular velocity. The present code applies to an unducted propeller operating in a regime in which the vortex sheet is always convected downstream in one direction. Future improvements will include the ability to simulate a ducted propeller and fully-reversed flow where the wake is drawn back past the propeller blades.

The motivation for developing the simulation is to use it to design closed-loop thrust controllers for AUVs. The results of simulations show the significant effect of fluid dynamics on the thrust and torque. Because torque can be measured through its relation with motor current, our results indicate that torque could be used to construct an accurate observer for the flow velocity at the propeller blades which would account for the hydrodynamic effects on the thrust.

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